DATA MODEL INTEGRATION OF SPM TRANSPORT IN THE DUTCH COASTAL ZONE

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Abstract

Suspended Particulate Matter (SPM) is an important environmental parameter in coastal seas such as the North Sea. Our description and understanding of the complex dynamical SPM transport system can be much improved by means of an integration of remote sensing data and numerical modelling. SPM data products retrieved from MERIS RR ocean colour by VU-IVM, which include information on the uncertainty in the data, are very suitable to be used to update the Delft3D-WAQ sediment transport model in an Ensemble Kalman Filtering approach. The sediment transport model proper is provided with information on water motion from the Delft3D-Flow hydrodynamic model and with surface wave parameters from a combination of SWAN wave model data and wave buoy observations, such that a robust modelling system results. The robustness of both data and model are prerequisites for a successful Kalman Filtering. Eventually, the assimilation of the mostly daily MERIS observations enables to overcome the limitations of cloud cover and restriction to the sea surface layer inherent to space borne ocean colour observations.

INTRODUCTION

Fine-grained suspended particulate matter (SPM) is composed of small particles of both organic and inorganic origin. SPM plays an important role in the ecology of shelf seas, for instance in the southern North Sea and adjacent Wadden Sea and estuaries. SPM influences the underwater light climate, which is an important environmental condition for plankton growth. The organic content of fine sediments is also an important food source at the basis of the food web.

Traditionally, monitoring has been based on regular ship cruises, occasionally extended with dedicated field campaigns. Consequently, our observation-based description of the coastal SPM transport system has often been limited to spatial and temporal scales of tens of kilometres and weeks, respectively, missing smaller scale spatial features or temporal events. However, with the arrival of reliable ocean colour remote sensing data (e.g., from SeaWiFs in 1997, and more recently, NASA’s MODIS sensors and ESA’s MERIS sensor) synoptic mapping of seas surface SPM has become feasible with increasing spatial resolution. Also, automated in situ monitoring buoys enable the recording of continuous time series of SPM at specific sites for prolonged periods of time. These developments enable a new level of describing and understanding the physical and biological dynamics in coastal seas including SPM transport (see e.g. Robinson et al., 2002). Part of this development is the extended use of numerical transport models, for combining all these observational data resources enables the operational use of numerical models for various water quality applications. In recent years, integrated observation-modelling efforts have been and are undertaken to further describe and understand the coastal system exploiting the new sources of information available (e.g., Gerritsen et al. 2000, Gayer et al, 2006, De Boer et al, 2007, Allen et al, 2007, Fettweiss et al, 2007).
In this paper we describe the application of the combination of remotely sensed SPM and derived remote sensing products and an SPM transport model of the southern North Sea to support assessment of SPM conditions in the Dutch coastal zone. This paper is part of a study that aims to increase our level of description and understanding of the coastal SPM transport with an application to support policy and decision making related to human interventions in the coastal system (such as infrastructure works, dredging and dumping etc.). Eventually, we wish to improve our means of detecting trends in SPM conditions and help distinguishing between natural and anthropogenic changes in the SPM (and eventually also in the ecosystem) in coastal waters.

The authorities of the Port of Rotterdam are preparing the extension of the present Maasvlakte land reclamation at the mouth of the Rhine outflow (see Figure 1). This reclamation is projected to be developed between 2008 and 2013 and eventually will comprise a 2 million square meter surface. For the construction, about 300 million cubic meters of sand is to be extracted from the seabed just offshore of the reclamation site. The mining of the sand will cause additional resuspension of silt fractions present in the upper layers of the sea bed. Especially since the mining may take place on a considerable scale and intensity, enhanced turbidity of the coastal waters cannot be ruled out. The increased turbidity may affect the underwater light climate and foraging of juvenile fish.

Figure 1: (left) MODIS (Terra) recording of the southern North Sea, March 26, 2007, illustrating spatial distribution of suspended matter in the surface water. Rectangle indicates the location of the Port of Rotterdam harbour extension Maasvlakte. (Image courtesy MODIS Rapid Response Project NASA/GSFC); (right) Outline of the projected Maasvlakte extension (purple), seaward of the existing (pink) land reclamation.

In order to determine any future effect of the construction (but also of the presence) of the land reclamation, it is essential to establish the baseline (reference) situation of the transport of SPM along the Dutch coastal zone. The SPM transport system, however, is characterised by highly variable concentrations in time and space: resuspension events during high wave conditions, formation of eddies and meanders, variable river inflow all contribute to the complexity. An illustration of the high temporal variability is obtained from high-resolution in situ measurements by means of Optical Backscattering Sensors (OBS) mounted on a Smartbuoy deployed by Cefas (Lowestof, UK) and the Dutch Rijkswaterstaat in 2001 (see Figure 2).
Figure 2. Time series of SPM surface concentration observed by the OBS on the Cefas-RIKZ Smartbuoy mooring 10 kilometers off Noordwijk (40 km north of the Maasvlakte). Dashed red line denotes temporal mean.

Analysis of these data has shown that, in the Dutch coastal zone, autocorrelation time scales are of the order of 7 days. Spatial correlation scales are estimated to be several tens of kilometres along coast but this has to be analysed in further detail in the near future.

Both *in situ* and remote sensing techniques will have their limitations when sampling such a heterogeneous system. *In situ* samples are mostly sparse in space and time, optical remote sensing will only measure a certain surface layer whereas a large portion of the SPM is found near the bed. To overcome the practical limitations to either source of information, we assimilate remotely sensed SPM concentrations in a numerical transport model by means of Ensemble Kalman Filtering (EnKF) (Evensen, 2003). At the present stage, we aim to assess the feasibility of applying EnKF for the abovementioned purposes and wish to indicate further future applications. This paper describes the overall objectives of the study and the model application. Two companion papers Eleveld et al. (2007) and El Serafy et al. (2007) discuss the developments in the SPM retrieval from the MERIS reflectance data and the EnKF data assimilation, respectively.

**APPROACH**

The approach to make optimal use of remote sensing data, model applications and in situ data is outlined below in Figure 3. In the present study, the year 2003 serves as a test case. For this entire year, MERIS Reduced Resolution water leaving radiance data have been processed by VU-IVM, using the HYDROPT algorithm (Pasterkamp and Van der Woerd, 2007). As discussed in further detail by Eleveld et al. (2007), these data have been extensively quality checked and various error products (in the scheme collectively indicated by $\sigma_{SPM}$) and the extinction coefficients ($K_{d560}$) have been determined and analysed. These additional data products provide indispensable information for the data assimilation, as discussed in more detail by El Serafy et al. (2007). The SPM and related data are used to continuously update the SPM transport model solution, hereby exploiting the now known uncertainties in the remotely sensed SPM data together with model uncertainties assessed from ensemble run experiments. Eventually, the assimilated model result of SPM concentrations (covering the entire year and extension over the vertical) and associated extinction coefficient will be compared against in situ field data from various sources to assess whether a closer description of the system is obtained. Finally, SPM transport fluxes may be determined from the model as well.

**MODEL DESCRIPTION**

The numerical model suite applied comprises the Delft3D Flow hydrodynamic model (Lesser et al., 2004), the surface wave model SWAN (Booij et al., 1999) and the sediment transport and water quality model Delft3D-WAQ (e.g., Van Gils et al. 1993, Los et al, 2006) These models are applied on a domain covering the southern North Sea (see Figure 4). The horizontal grid spans 65 columns x 134 rows. horizontal resolution is highest in the coastal areas of interest, notably the Dutch coastal zone (up to ~ 2x2 km). The grid is coarser in the outer parts of the area included in the model (down to ~
20x20 km). In the vertical 10 s-layers are applied. Near the bed and near the surface, the layer thickness is about 4 percent of the local water depth to enable good resolution of the surface mixing layer and the elevated near-bed SPM concentrations. At mid-depth, the layer thickness is approximately 20 percent of the local water depth.

**Figure 3.** Scheme of the data-model integration applied to obtain improved accuracy data sets of SPM concentrations and associated fluxes and extinction coefficients.

**Figure 4.** Horizontal grid of the Southern North Sea model applications, together with the bathymetry. The individual hydrodynamic, wave and transport models all operate on the same grid.
The water motion is governed by tidal, wind and density effects. Astronomic tides have been prescribed at the open boundaries. Atmospheric forcing has been derived from hindcasts of an limited area atmospheric model (HIRLAM, KNMI, see also http://hirlam.org). In addition, point sources where rivers discharge fresh water have been prescribed.

Resuspension due to surface waves, especially during strong wind events, is a key factor determining the SPM concentrations in the coastal seas. In order to obtain a model that describes the patterns of resuspension as accurate as possible given its resolution, appropriate wave height and period data are required as input. In order to achieve the desired accuracy, a data-model integration technique has been applied in which wave buoy observations are combined with the SWAN wave model results. The temporal evolution of the relevant wave parameters has been obtained from 6 wave buoys in the southern North Sea and the spatial interpolation is carried out with the aid of the spatial patterns in wave parameters derived from a SWAN wave model simulation for 2003. Figure 5 illustrates the spatial distance weight function and the annual mean significant wave height from SWAN.

The sediment transport model Delft3D-WAQ computes the dispersion of suspended matter in two different silt fractions given the transport velocities, mixing coefficients and bed shear stresses received from the hydrodynamic and wave models. Recently, Delft3D-WAQ has been extended with an improved parameterization of the resuspension and buffering of silt fractions from and in a predominantly sandy seabed (Van Kessel et al., 2007). This parameterization enables a realistic description of the periodic and relatively limited resuspension during the tidal cycle and the massive resuspension from deeper bed layers observed during high wave events.

The transport model is provided with lateral boundary conditions based on climatological SPM concentrations, SPM loads from the rivers and specific point or line sources representing erosion of cliffs (e.g. off East Anglia) and the Flemish Banks. The model solution for 2003 is based on a multi-annual model experiment using water motion and wave information from 1996 onward. During the preparation of this experiment the solution, especially the slowly responding bed composition has been properly equilibrated.

**FIRST RESULTS**

First results of the assimilation of MERIS-derived SPM into Delft3D-WAQ are encouraging. Updating of the model solution (state) has been carried out successfully. The SPM concentrations and error information have been gridded onto the computational grid of Delft3D WAQ (see also Figure 6 below).
Consequently, an appropriate spatial aggregation level has been obtained, as it is not feasible and even undesirable to attempt to capture all individual small-scale structures due to eddies and meanders. Since remote sensing data are available nominally once (max twice) per day, the forward model integration between the updates provides a temporal and spatial interpolation on the appropriate scales. Further details of the assimilation procedure, the inclusion of the additional information on the quality parameters that guide the acceptance and weighing during spatial averaging and updating of the model state and the first assimilated results, are presented by El Serafy et al. (2007).

The panels in Figure 6 right and below illustrate the effect of the gridding of the MERIS-derived SPM data and illustrates the correspondence between this gridded product and the model results prior to assimilation for a particular day in 2007. Obviously, different instances during the year may yield lower spatial coverage by the earth observation and less agreement between model and observations. Nevertheless, this illustrates that on the spatial aggregation scale dictated by the model, the remote sensing data yield comparable information about the main features. The local maxima of SPM concentration off the coast of Belgium and the south of The Netherlands, the elevated concentrations off the coast of East Anglia and in the German Bight are clearly observed in both sources of information. However, meanders and eddies resolved in the original, reduced resolution MERIS data are lost upon gridding.

Figure 6. Top right: SPM surface concentration (February 17, 2003, 10:46 UTC) derived from MERIS Reduced Resolution imagery by Eleveld et al. (2007). Bottom right: same data averaged to the Delft3D model grid. Bottom left: daily mean SPM concentration (top layer) for February 17, 2007 as computed by the sediment transport model prior to assimilation. The colour scale is identical for all three panels.
CONCLUSIONS

From the experiments discussed here and in El Serafy et al. (2007), we conclude that assimilation of MERIS derived SPM into a sediment transport model is technically feasible. Thanks to the additional error information on the remote sensing data, the EnKF can be successfully applied. The procedure seems suited to reach a solution that is consistent not only with the model equations, but also with general notions of the coastal system. Using a 3D transport model enables the interpolation in horizontal (underneath clouds) and time (between overpasses) as well as extrapolation over the vertical into the unobserved subsurface.

Applying this type of data assimilation for an entire year or even multiple years will extend the description of the coastal system in a physically consistent way suitable for baseline determination. Nevertheless, there are uncertainties and challenges to be dealt with: remote sensing is limited to the surface layer, whereas the bulk of the sediment is often found near the bed. This source of uncertainty will be attempted to be minimized by applying additional information on the optical depth (see Eleveld et al, 2007 and El Serafy et al 2007) and as such control an extended part of the model solution. This will eliminate any possible mismatch between the observed and modelled SPM mass within the visible depth interval.

A final step is objective quantitative assessment of the improvements obtained by application of the data assimilation. For this, we plan to adopt the method presented by Taylor (2001) who devised an objective measure for model skill depending on standard deviations of model and validation data, model-data correlation coefficient and the maximum potentially achievable correlation given the stochastic nature of the solution. Since the spatio-temporal scales of SPM in the coastal zone vary widely and stochastic patterns may be found that can only partly be resolved by the numerical models, a limit is to be expected as to what goodness of fit is achievable at all.

In order to fully assess the value of the data-assimilation as described above, a follow-up study is recommended in which the 2007 conditions are to be simulated and validated against field data recently and currently collected by the Port of Rotterdam.

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